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# Impact Resistance of Shear-strengthened RC Beams with Sprayed GFRP

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**ABSTRACT:** The use of Sprayed Glass Fiber Reinforced Polymer (GFRP) was investigated as a potential technique for improving the impact resistance of reinforced concrete (RC) beams strengthened in shear. Reinforced concrete beams with a small number of stirrups as shear reinforcement were retrofitted. Different configurations and thicknesses of Sprayed GFRP with a random distribution of chopped fibers, at a fiber content of about 25% by volume, were applied on two or three sides of the RC beams. These specimens were then subjected to impact using a fully instrumented 14.5 kJ drop weight impact machine. A frequency of 100,000 Hz was used to collect the dynamic data. Results indicate that RC beams with the Sprayed GFRP coating were highly resistant to impact. RC beams with the sprayed GFRP coating were found to possess a higher load carrying capacity, and were found to absorb much greater energy compared to those without the coating, under both static and impact loading.

Keywords: sprayed GFRP, impact, shear, beam, reinforced concrete, retrofit.

## 1. INTRODUCTION

This paper deals with shear strengthening of RC beams using Sprayed GFRP composites. This technique as compared to externally bonded FRP fabrics and laminates is quite new for strengthening of RC structures. Hence, a limited number of publications are available with respect to this technique [1], [2]. On the other hand, externally bonded FRP including glass, carbon, and aramid (e.g. Kevlar) fibers have been studied for flexural and shear strengthening of RC beams and strengthening of RC columns extensively. Fundamentally, all of these techniques (i.e. fabric, laminate, and spray) are alike in that all involve the attachment of extra reinforcement (i.e. FRP composite) to the surface of an existing RC member. There are only a limited number of studies available where RC beams strengthened with externally bonded FRP were investigated under impact loading [3]–[6].

## 2. SPRAYED GFRP APPLICATION AND PROPERTIES

A Venus-Gusmer H.I.S. Chopper Unit equipped with a ‘Pro Gun’ spray gun was used in this research. It is portable equipment and can be used easily on-site. This system contains three major parts; a resin pump which pumps the polyester resin from the drum, a catalyst pump which pumps the Methyl Ethyl Ketone Peroxide (MEKP) to the nozzle, and a spray/chopper unit. To run this equipment, a compressed air source with a minimum capacity of 0.5 $m^3$/minute is required. The resin and the catalyst are separately transported into the spray gun. They do not come into contact until they reach the mixing nozzle at the front of the gun. At the nozzle, there are inlets for air and the solvent. Air powers the chopper unit and the solvent is used to flush the resin and catalyst at the end of each period of operation. The glass fibers in the form of roving (i.e. a large number of fibers bundled together) are brought to the chopper unit. One of the rollers inside the chopper unit has evenly spaced blades which cut the glass fibers into a prespecified length. By changing this roller (i.e. the number of blades on the roller) the length of the chopped fibers can be changed. The chopper unit used in this research project was able to produce chopped fibers from 8 to 48 mm in length. These chopped fibers are forced out by air flow. The rotation of the rollers inside the chopper unit also helps a smooth flow of fibers. The gun sprays the mixture of resin and catalyst with the chopped fibers onto the spraying surface. A spring steel roller is used to force out the entrapped air voids and to produce a consistent thickness. The final product is a 2-D randomly distributed fibers encapsulated by a catalyzed resin.

In this research study, GFRP was sprayed by skilled nozzlemen throughout the research and as a result the quality and properties of sprayed materials were consistent. A constant length of 32 mm was used for chopped fibers in Sprayed GFRP composites in this research study. Using ASTM D2584, the average density of final cured Sprayed GFRP composite was found to be 1473 kg/$m^3$ with a Coefficient of Variation of 0.9%. ASTM D2584 was also used to determine the fiber volume fraction of Sprayed GFRP composites. Fiber volume fraction for final cured Sprayed GFRP composite was found to be 24.7% with a Coefficient of Variation of 1.5%. Sprayed GFRP coupons were tested using a Baldwin 400 kip Universal Testing Machine to evaluate the tensile properties which are tabulated in Table 1.

Table 1: Sprayed GFRP properties

| Tensile Properties | Value | Unit |
|---|---|---|
| Ultimate Tensile Strength | 69 | MPa |
| Tensile Modulus | 14 | GPa |
| Ultimate Rupture Strain | 0.63 | % |

## 3. DROP WEIGHT IMPACT MACHINE

A drop weight impact machine with a capacity of 14.5 kJ was used in this research study. A mass of 591 kg (including the striking tup) can be dropped from as high as 2.5 m. During a test, the hammer is raised to a certain height above the specimen using a hoist and chain system. At this position, air brakes are applied on the steel guide rails to release the chain from the hammer. By releasing the breaks, the hammer falls and strikes the specimen. Three load cells were designed and built at the University of British Columbia for this research project. During the preliminary tests, it was discovered that if the specimen was not prevented from vertical movements at the supports, within a very short period of first contact of hammer with the specimen, contact with the support was lost and as a result, loads read by the support load cells were not correct. This phenomenon was further verified by using a high speed camera (1700 frames per second). As a result loads recorded by the support load cells for two identical tests were totally different. To overcome this problem, the vertical movement of RC beams at the supports was restrained using two steel yokes (Fig. 1). In order to assure that the beams are still simply supported, these yokes are pinned at the bottom, to allow rotation during beam loading. To allow an easier rotation, a round steel bar was welded underneath the top steel plate where the yoke touched the beam.

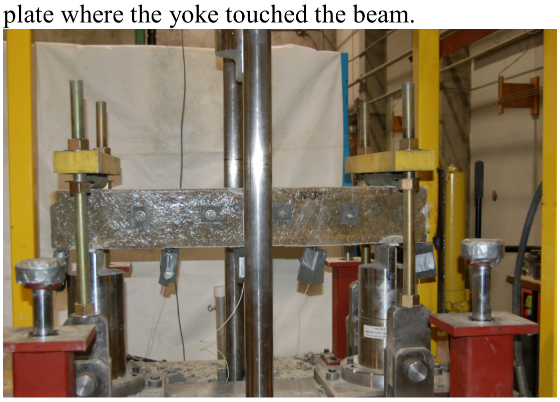

Figure 1. Impact test setup with steel yokes

## 4. TEST RESULTS

A total of 15 identical RC beams (Fig. 2) were cast to investigate their behavior under impact loading with and without Sprayed GFRP as external shear reinforcement. Three beams were tested under impact with 600 mm and 800 mm drop height (impact velocity of 3.43 m/s and 3.96 m/s, respectively). The remaining 12 beams were strengthened with Sprayed GFRP and tested under impact loading. One beam was tested with an impact velocity of 3.43 m/s, while others were tested with 3.96 m/s impact velocity. Table 2 tabulates the beams designation and configuration. This RC beam (with Φ4.75 stirrups @ 160 mm) was tested under quasi-static loading and its load carrying capacity was about 91.6 kN. It is also worth noting that the beam was designed to produce a typical shear failure mode since not enough stirrups were provided and shear strength of concrete was far below the flexural strength of the beam.

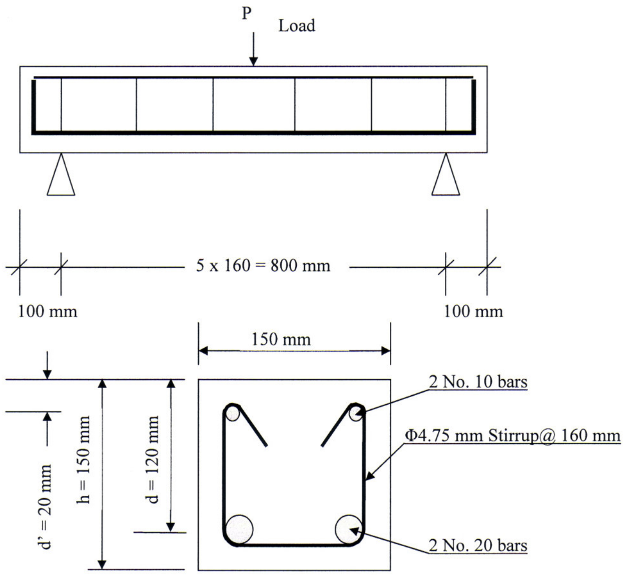


Figure 2. RC beam details and cross-section

Table 2: RC beams designations and details

| Beam Designation | Drop Height (mm) | Sprayed GFRP Width (mm) | Sprayed GFRP Thickness (mm) | | |
|---|---|---|---|---|---|
| | | | 2 Sided | 2 Sided + 4 Bolts | 3 Sided |
| PI-600 | 600 | NA | ----- | ----- | ----- |
| PI-800-1 | 800 | NA | ----- | ----- | ----- |
| PI-800-2 | 800 | NA | ----- | ----- | ----- |
| SI-2S-800-1 | 800 | 150 | 3.3 | ----- | ----- |
| SI-2S-800-2 | 800 | 150 | 4.6 | ----- | ----- |
| SI-2S-800-3 | 800 | 150 | 6.5 | ----- | ----- |
| SI-2S-800-4 | 800 | 150 | 10.3 | ----- | ----- |
| SI-4B-800-1 | 800 | 150 | ----- | 2.4 | ----- |
| SI-4B-800-2 | 800 | 150 | ----- | 4.0 | ----- |
| SI-4B-800-3 | 800 | 150 | ----- | 6.5 | ----- |
| SI-3S-800-1 | 800 | 150 | ----- | ----- | 1.9 |
| SI-3S-800-2 | 800 | 150 | ----- | ----- | 2.8 |
| SI-3S-800-3 | 800 | 150 | ----- | ----- | 3.2 |
| SI-3S-800-4 | 800 | 150 | ----- | ----- | 6.2 |
| SI-3S-600 | 600 | 150 | ----- | ----- | 10.7 |

Note: **P**: Plain RC beam (no Sprayed GFRP was applied), **I**: Tested under Impact loading, **S**: Sprayed GFRP was applied as external shear reinforcement, **2S**: Sprayed GFRP was applied on 2 lateral Sides of the beam, **4B**: 4 through Bolts (threaded No. 10 bars @ 175 mm) were used as mechanical fasteners, **3S**: Sprayed GFRP was applied on 3 lateral Sides of the beam.

For all impact tests using the drop-weight machine, PCB Piezotronics™ accelerometer was employed. It was screwed into a mount which was glued to the specimens' mid-span prior to testing. The velocity and displacement histories at the location of accelerometer were obtained by integrating the acceleration history with respect to time. Accelerations, striking load at the tup load cell as well as reaction forces at the support load cells were recorded with a frequency of 100 kHz using National Instruments™ VI Logger software. It is known that a part of the tup load is used to accelerate the beam from its rest position [7]. Therefore, loads measured by the instrumented tup will result in misleading conclusions due to inertia effect. To overcome this problem, true bending load at time *t*, which acts at the mid-span, can be obtained by adding the reaction forces at the support anvils at time *t*. This was used to get bending load versus mid-span deflection curves for RC beams tested under impact loading in this study.

To enhance the concrete-FRP bond, concrete surface was roughened using a small pneumatic concrete chisel prior to FRP application. Through-bolts and nuts were also used in three beams as mechanical fasteners to prevent premature failure due to FRP debonding.

Load carrying capacity (i.e. maximum recorded true bending load or summation of support load cells) of all RC beams with and without retrofit is plotted in Fig. 3. Several RC beams (Fig. 2) were also tested under quasi-static loading with and without Sprayed GFRP as external shear reinforcement to compare the load rating effects on their shear behavior. Load carrying capacities of similar beams are compared in Fig. 4. As expected, the highest increase in load carrying capacity is achieved by Sprayed GFRP on 3 sides. This figure shows that Sprayed GFRP is definitely a promising technique in enhancing impact resistance of RC beams. It also proves that the composite material should be applied on 3 sides of the beam, wherever possible to gain the maximum benefits out of this material. Note that the thickness of composite material for the RC beam strengthened on its 3 sides, although quite similar to other beams, was the smallest among all the strengthened RC beams shown in Fig. 4.

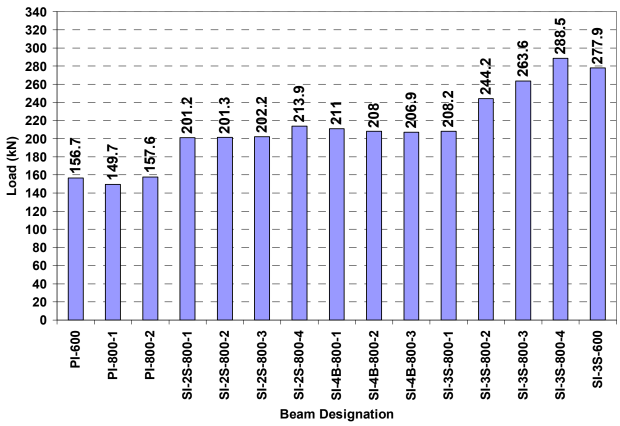


Figure 3. Load carrying capacity for different plain and strengthened RC beams

## 5. CONTRIBUTION OF SPRAYED GFRP IN DYNAMIC SHEAR STRENGTH OF RC BEAMS

The dynamic shear contribution of Sprayed GFRP is tabulated in Table 3 for strengthened RC beams tested under impact loading. The beams tested under the same drop height of 800 mm are compared in this Table. It is seen that while increasing the thickness of Sprayed GFRP when applied on 3 sides increased the contribution of Sprayed GFRP in shear strength of RC beams under impact loading, it was not effective in RC beams with Sprayed GFRP on 2 sides, with or without mechanical fasteners. In all tests performed in this study, the Sprayed GFRP fracture did not occur at the location of the shear cracks. This, in turn, showed that after a certain strain in Sprayed GFRP, which was clearly less than its strain at rupture, there would be no contribution of this composite to dynamic shear strength of RC beams. Therefore, for Sprayed GFRP applied continuously on both sides of an RC beam with a thickness of $t_{frp}$ on each side and a dynamic modulus of elasticity of $E_{frp\_d}$, the product of $2 \times t_{frp} \times d_{frp} \times E_{frp\_d} \times \varepsilon_{frp}$ will give the shear resisted by the Sprayed GFRP under impact loading:

$$V_{frp\_d} = 2 t_{frp} d_{frp} E_{frp\_d} \varepsilon_{frp} \quad (1)$$

where,

$V_{frp\_d}$= dynamic contribution of Sprayed GFRP in shear strength of RC beam [N]

$t_{frp}$ = average thickness of the Sprayed GFRP [mm]

$d_{frp}$ = depth of FRP shear reinforcement [mm]

$E_{frp\_d}$ = dynamic modulus of elasticity of Sprayed GFRP composite [MPa]

$\varepsilon_{frp}$ = 0.003 (effective strain of Sprayed GFRP for continuous U-shaped around the bottom of the web)

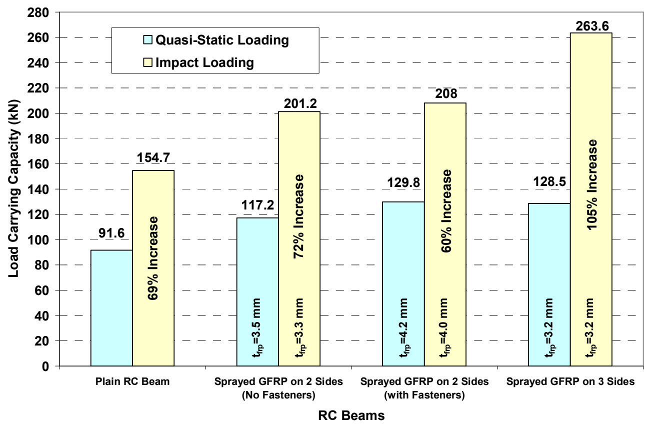


Figure 4. Load carrying capacity, static vs. impact

It is worth mentioning that $\varepsilon_{frp}$, the maximum strain of GFRP at which the integrity of concrete and secure activation of the aggregate interlock mechanism are maintained, was found to be 0.003 from a series of tests performed on shear strengthened RC beams using Sprayed GFRP under quasi-static loading . Dynamic contribution of Sprayed GFRP to shear strength for RC beams with FRP on 3 sides vs. $2 \times t_{frp} \times d_{frp}$ product, using Table 3, is shown in Fig. 5. This figure shows that the contribution of Sprayed GFRP in dynamic shear strength of RC beams may stay at a constant level beyond a certain thickness of Sprayed GFRP. This, in turn, may also explain why the dynamic shear contribution did not increase by increasing the Sprayed GFRP thickness in 2-sided beams; all the thickness tested here may have been greater than the threshold thickness for 2-sided beams. In other words, in RC beams with Sprayed GFRP on their 3 sides, this threshold thickness seems to be much greater than that for the 2-sided beams.

Table 3: Dynamic contribution of sprayed GFRP in shear strengthening of RC beams

| Sprayed GFRP Configuration | Beam (1) | Peak Load [kN] (2) | Peak Load of Control Beam [kN] (3) | Dynamic Contribution of Sprayed GFRP in Shear Strength [kN] ((2)-(3)) (4) | $d_{frp}$, Effective depth of FRP [mm] (5) | $t_{frp}$, FRP Thickness [mm] (6) |
|---|---|---|---|---|---|---|
| Sprayed FRP on two sides with no mechanical fasteners | SI-2S-800-1 | 201.2 | 154.7 | 46.5 | 120 | 3.3 |
| | SI-2S-800-2 | 201.3 | 154.7 | 46.6 | 120 | 4.6 |
| | SI-2S-800-3 | 202.2 | 154.7 | 47.5 | 120 | 6.5 |
| | SI-2S-800-4 | 213.9 | 154.7 | 59.2 | 120 | 10.3 |
| Sprayed FRP on two sides with mechanical fasteners | SI-4B-800-1 | 211 | 154.7 | 56.3 | 120 | 2.4 |
| | SI-4B-800-2 | 208 | 154.7 | 53.3 | 120 | 4 |
| | SI-4B-800-3 | 206.9 | 154.7 | 52.2 | 120 | 6.5 |
| Sprayed FRP on three sides | SI-3S-800-1 | 208.2 | 154.7 | 53.5 | 120 | 1.9 |
| | SI-3S-800-2 | 244.2 | 154.7 | 89.5 | 120 | 2.8 |
| | SI-3S-800-3 | 263.6 | 154.7 | 108.9 | 120 | 3.2 |
| | SI-3S-800-4 | 288.5 | 154.7 | 133.8 | 120 | 6.2 |

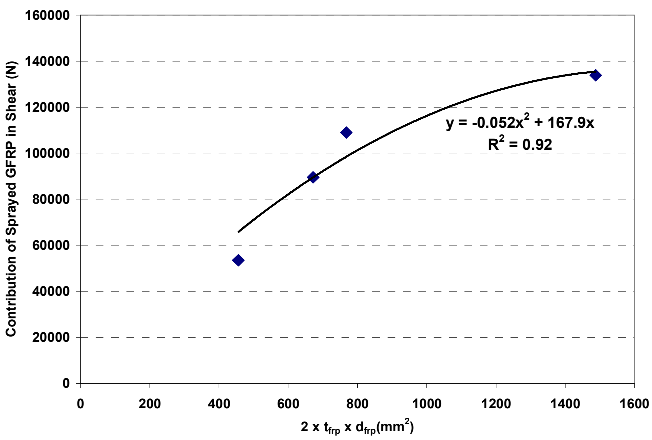


Figure 5. Contribution of sprayed GFRP in shear vs. $2 \times t_{frp} \times d_{frp}$ for RC beams with sprayed GFRP on 3 sides

Assuming $\varepsilon_{frp}$ remains unchanged in both static and impact loading, $E_{frp\_d}$, dynamic modulus of elasticity of Sprayed GFRP composite, and $DIF_{frp}$, Dynamic Increase Factor for modulus of elasticity of Sprayed GFRP are calculated and results are reported in Table 4.

$DIF_{frp}$ is calculated as follows:

Table 4: $DIF_{frp}$ for RC beams with sprayed GFRP on their 3 sides

| Beam (1) | $E_{frp\_d} \times \varepsilon_{frp}$ (MPa.mm/mm) (2) | $\varepsilon_{frp}$ (mm/mm) (3) | $E_{frp\_d}$ (MPa) (4)=(2)/(3) | $E_{frp}$ (MPa) (5) | $DIF_{frp}$ (6)=(4)/(5) |
|---|---|---|---|---|---|
| SI-3S-800-1 | 117.3 | 0.003 | 39100 | 14000 | 2.79 |
| SI-3S-800-2 | 133.2 | 0.003 | 44400 | 14000 | 3.17 |
| SI-3S-800-3 | 141.8 | 0.003 | 47267 | 14000 | 3.38 |
| SI-3S-800-4 | 89.9 | 0.003 | 29967 | 14000 | 2.14 |

$$DIF_{frp} = \frac{E_{frp\_d}}{E_{frp}} \tag{2}$$

$DIF_{frp}$ = Dynamic Increase Factor for modulus of elasticity of Sprayed GFRP
$E_{frp\_d}$ = dynamic modulus of elasticity of Sprayed GFRP composite [MPa]
$E_{frp}$ = modulus of elasticity of Sprayed GFRP composite [MPa]

Combining (1) and (2), the following equation is proposed to calculate the dynamic contribution of Sprayed GFRP in shear strength of RC beam (U-shaped Sprayed GFRP):

$$V_{frp\_d} = 2t_{frp} d_{frp} DIF_{frp} E_{frp} \varepsilon_{frp} \tag{3}$$

It should be noted that $V_{frp\_d}$ in (3) was derived assuming that under impact loading, the effective strain of Sprayed GFRP, $\varepsilon_{frp}$ was the same as that one under static loading. Since this strain is the maximum strain of Sprayed GFRP at which the integrity of concrete and secure activation of the aggregate interlock mechanism are maintained, the above assumption seems to be a reasonable one.

It is worth mentioning that $DIF_{frp}$, which was considered to be an increase factor for modulus of elasticity of FRP under dynamic loading, can also be assumed an increase factor for effective stress of FRP (i.e. $E_{frp}\varepsilon_{frp}$) under dynamic loading. $DIF_{frp}$ is a function of dynamic-stress-rate to static-stress-rate ratio. This ratio was found to be about $10^6$ for the tests performed in this study and the dynamic increase factor was between 2.14 to 3.38. Further investigations are required to determine the actual value of $DIF_{frp}$ for different types of Sprayed GFRP and to establish a relationship between $DIF_{frp}$ and the dynamic-stress-rate to static-stress-rate ratio.

## 6. ENERGY EVALUATION

The energy expended in deflecting and fracturing the beam is calculated from the area under the bending load vs. deflection curve and compared with energy stored in (or released by) the dropping hammer. The results are shown in Fig. 6. In this study, the ratio of absorbed energy to input energy (energy absorbed by the beam to incident energy in the hammer) was in the range of 80% to 98% with a mean value of 91%. Therefore, one can conclude that about 91% of the input energy was absorbed by the RC beam.

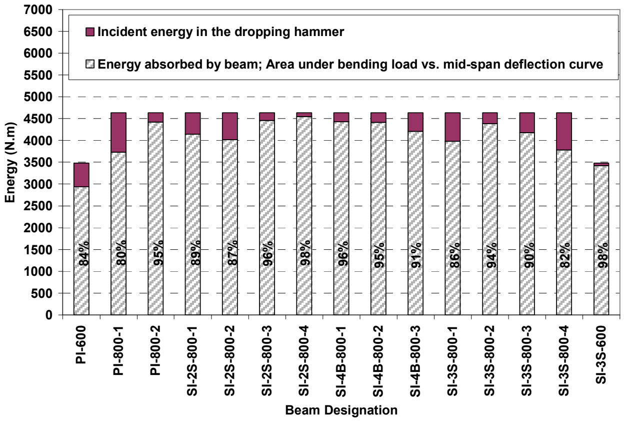


Figure 6. Energy Balance for Different Plain and Strengthened RC Beams

## 7. CONCLUSIONS

Based on the results and discussions reported here, the following conclusions can be drawn:

1. Sprayed GFRP was an effective material to increase shear capacity of RC beams under impact loading.
2. Shear load capacity of plain RC beam without retrofit under impact loading was about 1.7 times of its static capacity for the conditions and details of tests performed here.
3. When RC beams were strengthened by Sprayed GFRP on their lateral sides (2-sided retrofit), increase in FRP thickness did not increase the load carrying capacity under impact loading and this was true for both cases: with and without mechanical fasteners. Shear load capacity of above mentioned strengthened RC beams under impact loading were about 1.7 times and 1.6 times of their static capacity for beams without and with mechanical fasteners, respectively, for the conditions and details of tests performed here.
4. When RC beams were strengthened by Sprayed GFRP on their three sides (U-shaped), increase in FRP thickness increased the load carrying capacity under impact loading. Shear load capacity of above mentioned strengthened RC beam under impact loading was about 2.1 times its static capacity for the conditions and details of tests performed here.
5. Sprayed GFRP under impact loading possessed a higher modulus of elasticity or at least a higher effective stress (i.e. $E_{frp}\varepsilon_{frp}$) compared with that under static loading. An equation was proposed to calculate the dynamic contribution of Sprayed GFRP in shear strength of RC beam based on the dynamic stress rate. Further investigations are required to determine the dynamic increase factor for different types of Sprayed GFRP.

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